A review of Australian approaches for monitoring, assessing and reporting estuarine condition: I. International context and evaluation criteria

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Abstract

Given the immeasurable value of estuaries and their severe and growing pressures, sound understanding and reporting of estuarine condition is essential for their effective management and sustainable development. In light of this, we aim to provide a timely and comprehensive three-part review of the approaches currently employed for monitoring, assessing and reporting estuarine condition, focussing on Australian systems. Here, in Part 1, we establish the national and international context of our review and define globally-relevant evaluation criteria against which to assess Australian progress. We achieve this by examining effective monitoring, assessment and reporting programs from around the world and characterising ‘best practice’. We then highlight the Australian historical context and consider recent policies, frameworks, guidelines and legislation relating to the monitoring and reporting of estuarine condition nationwide.

Keywords Estuary, ecological status, health, monitoring, management, Water Framework Directive

1. Introduction

Estuaries worldwide provide critical support for coastal and marine biodiversity. They also provide extensive and often irreplaceable ecosystem services, including food security, flood mitigation, water filtration, nutrient cycling, power generation, amenity and cultural significance (Kennish, 2002; McLusky and Elliott, 2004; Barbier et al., 2011), as evidenced by the fact that 22 of the 32 largest cities in the world are located around estuaries (Valle-Levinson, 2010). The close link between these ecosystems and major population centres, combined with their geological setting as receiving waters at the terrestrial, riverine and marine interface, makes estuaries extremely vulnerable to anthropogenic pressures and consequent degradation (Lotze et al., 2006; Barbier et al., 2011). Indeed, in a global assessment of coastal and marine ecosystems, estuaries were listed among the 'critically endangered' (Jackson, 2008), reflecting the cumulative impacts of pollution (including nutrient and organic carbon enrichment and chemical contamination), habitat loss and alteration, overfishing, freshwater diversions or other hydrological modifications, and introduced species (Jackson et al., 2001; Kennish, 2002; Worm et al., 2006; Jackson, 2008). Additionally, the synergistic effects of climate change are likely to increase many of these pressures, leading to enhanced and potentially unpredictable impacts on estuarine ecology (Gillanders et al., 2011; Hobday and Lough, 2011; Statham, 2012). For example, reductions in rainfall and stream flows are predicted to impact water resources, including the condition of aquatic and riparian ecosystems, in numerous regions with a semi-arid Mediterranean climate (Ali et al., 2012; Silberstein et al., 2012).

These pressures are significant in Australia, where an expanding population and competing demands are placing increasing strain on estuarine ecosystems. As of 2001, 85% of Australians lived within 50km of the coast (Australian Bureau of Statistics, 2004), and more than 90% of the projected increase in population by 2050 is expected to be focused on the coastal zone (Hirst, 2008). Much of this growth is predicted to occur in or around the eight Australian State and Territory capitals, of which seven are located on major estuaries. Additionally, in southern Australia, the climate has exhibited marked drying and warming trends, with resultant decreases in runoff and river flows that are predicted to continue in future decades (Hobday and Lough, 2011; Lough and Hobday, 2011). Yet, estuaries provide Australia's highest value biophysical resources in terms of ecosystem services and are critical for supporting Australian fisheries, food security, ports, industries, tourism, lifestyles and livelihoods (NLWRA, 2002a; Sheaves et al., 2014).

Given their high value and escalating pressures, effective management of estuaries, including monitoring and reporting of their condition, is essential to help ensure the sustainability of these ecosystems and the human populations they support. Within Australia, monitoring, assessment and reporting, of both resources/assets and program performance, are recognised as integral components of natural resource management programs. They enable the impacts, effectiveness and value of management actions to be evaluated and thus promote both greater accountability and improved targeting of management actions under an adaptive management framework (Hajkowicz, 2009; Williams, 2011). Therefore, natural resource management requires that we measure, track (monitor) and communicate the condition of those resources over time and space.

In light of the aforementioned pressures on the >900 estuaries throughout Australia (NLWRA, 2002a), we aim to provide a timely and comprehensive evaluation of the approaches currently employed across the nation for assessing, monitoring and reporting estuarine condition. This evaluation consists of three parts. In this first part we seek to establish the national and international context of our review and define globally-relevant evaluation criteria against which to assess Australian progress. The second part (Hallett et al., submitted II) reviews the specific approaches adopted in each Australian State/Territory. The third part of the review (Hallett et al., submitted III) synthesises and critically evaluates the successes and obstacles encountered across the States/Territories, highlights examples of best practice across Australia, and concludes with recommendations for more effective assessment, monitoring and reporting of estuarine condition, both across Australia and internationally.

We begin this first part by briefly defining some key terms and the scope of the review (Section 1), then examine effective estuarine monitoring, assessment and reporting programs from around the world in order to characterise ‘best practice’ and provide a sound basis against which current Australian approaches can be assessed (Section 2). In Section 3, we highlight the historical context and importance of our review and, finally, consider recent Australian policies, frameworks, guidelines and legislation relating to the monitoring and reporting of estuarine condition.

1.1. Defining and classifying estuaries

The long-running debate over how best to define an estuary has been reviewed elsewhere (Elliott and McLusky, 2002; McLusky and Elliott, 2007; Potter et al., 2010) and to add to this debate is unnecessary in the current review. In seeking to compare approaches across Australia and internationally, the current review takes an all-encompassing view, and considers an estuary to be any system that has been so-defined under a relevant monitoring program.

A wide range of estuary types exists throughout Australia, due in part to the geographical scale of the country and accompanying variations in climate, oceanography, geology and tidal regime (Wolanski, 2014). Numerous authors have proposed schemes for classifying Australian estuaries on the basis of geomorphology, climatic zones, tides, waves and other physical factors (Heap et al., 2001). Australian estuaries include coastal inlets, embayments, deltas, tidal creeks and flats, floodplains, strandplains, drowned river valleys, seasonally-open or normally-closed barrier estuaries and Intermittently Closed and Open Lakes and Lagoons (Barton, 2003). For a broad overview of the diversity of estuary types across Australia, see NLWRA (2002a, b).

1.2. Estuarine condition, health or status

Terms such as 'health', 'status', 'integrity' and 'quality' are now widely used and debated in reference to the condition of ecosystems and natural resources (Tett et al., 2013). However, each essentially reflects the degree to which an ecosystem or resource has been degraded from some desired endpoint or reference (e.g. a natural, pristine state). For the purposes of this review the above terms are considered synonymous.

Ideally, any assessment of ecosystem condition should be holistic and consider the extent to which appropriate (i) environmental conditions are maintained, (ii) species, populations and communities are present and (iii) rates and scales of ecological processes and interactions are occurring (Rapport, 1998). Particularly in estuaries, however, where the strength and variability of physico-chemical gradients are usually considerable, it can be difficult to distinguish natural from human-induced stress, i.e. the so-called Estuarine Quality Paradox (Elliott and Quintino, 2007). It is thus critical that measures of estuarine condition are benchmarked against robust reference or baseline conditions that adequately account for natural spatio-temporal variability, enabling true signals of anthropogenically-driven change to be detected against background 'noise'.

1.3. Monitoring, assessment and reporting

Monitoring of estuarine condition generally involves the routine or repeated measurement of physical, chemical and/or biological parameters to (i) quantify ecological status, (ii) detect and characterise human impacts, and/or (iii) evaluate ecosystem responses to management actions (Hirst, 2008). It is crucial that monitoring outputs are reported in an appropriate manner, rather than simply being made available as raw data, to allow them to be understood and utilised by managers, other stakeholders and the wider community. Numerous authors have summarised the benefits and requirements of effective monitoring programs, and also the key aspects of ineffective ones (e.g. Lovett et al., 2007; Lindenmayer and Likens, 2010; Elliott, 2011).

Monitoring approaches can take many forms, including surveillance, condition and investigative/diagnostic monitoring (de Jonge et al., 2006; Elliott, 2011). Surveillance monitoring is relatively broad-scale, characterised by a series of regular spatial and/or temporal surveys designed to quantify and track ecosystem condition (Hering et al., 2010). Condition monitoring, focused on a subset of ecosystem components/elements, seeks to provide further detail on the condition of water bodies suspected of failing to meet established standards and to verify *post-facto* if management measures are effective (Ferreira et al., 2007). Investigative/diagnostic monitoring involves detailed scientific study of specific stressor(s) and is thus perhaps more appropriately characterised as applied research than monitoring, *sensu stricto* (Ferreira et al., 2007). It is often used to determine the results of management measures or industrial processes such as dredging. For this reason, the current review largely focuses on the former two monitoring approaches. It also excludes programs addressing project-specific and often localized impacts, (e.g. Environmental Impact Assessments and industrial compliance monitoring), monitoring and reporting undertaken by community groups, and pure and applied research projects. However, we acknowledge the critical roles and value of each of these approaches for better understanding estuarine condition.

2. International context

Advances in monitoring techniques and approaches, in combination with progressive legislation and policy implementation, have led in recent decades to the emergence of an international consensus around how best to assess, monitor and report the condition of estuaries and other aquatic ecosystems. The attributes of these developing 'best-practice' approaches are summarised and exemplified in Table 1, and have been drawn largely from three jurisdictions (USA, Europe and South Africa) in which estuarine monitoring and reporting has progressed considerably in recent decades. They are intended to offer a robust set of criteria against which the progress of Australian approaches (and also those elsewhere) could reasonably be evaluated. A brief overview of the progress in each of the above jurisdictions is also provided below.

2.1. United States of America

In the USA, the Clean Water Act requires that the States report to the US Environmental Protection Agency (EPA) and the EPA reports to Congress on the condition of the nation's waters (US EPA, 2012). Accordingly, various strategies and programs were established under this legislation to address a previous lack of nationally consistent, comprehensive monitoring programs for assessing estuarine condition. These include, among others, the National

Coastal Assessment Program and the National Estuary Program of the US EPA, and the National Status and Trends and National Estuarine Research Reserve programs of the National Oceanic and Atmospheric Administration (NOAA) (Table 1). Outputs from these initiatives combine to inform national-level condition assessments, e.g. NOAA's National Estuarine Eutrophication Assessment (Bricker et al., 2007) and the US EPA's National Coastal Condition Assessment (NCCA).

Section 101 of the Clean Water Act requires federal and state agencies to restore and maintain the physical, chemical and biological integrity of the nation's waters, including its estuaries (Gibson et al., 2000). The inclusion of 'biological integrity' as a requirement of monitoring and reporting programs mandated by the Clean Water Act has led to a broader consideration of ecological condition, with five indices now being employed to assess coastal and estuarine status under the NCCA, i.e. water quality, sediment quality, benthic community condition, coastal habitat and fish tissue contaminants (Borja et al., 2012; US EPA, 2012; Table 1). Much of this progress towards holistic ecological assessment was made under the three-tiered Environmental Monitoring and Assessment Program of the US EPA Office of Research and Development (CRMSW, 2000), which collected field data from 1990 to 2006 and established guidelines for integrating biological measures alongside the more traditional chemical and physical assessments of estuarine condition (Gibson et al., 2000). Such a focus on biotic indicators was unusual among estuarine monitoring programs at the time (Lindenmayer and Likens, 2010).

2.2. Europe

Fundamental changes to water resource and aquatic ecosystem management across Europe were catalysed by the Water Framework Directive (WFD), which was adopted in 2000. The WFD placed aquatic ecology at the forefront of water management decisions (Hering et al., 2010), with legislative requirements for European Union (EU) Member States to consider the broader ecological status and integrity of aquatic biota in managing their inland and coastal waters (Borja, 2005; Table 1). Member States were legally required to achieve by 2015 'good' chemical and ecological status for all surface water bodies (i.e. rivers, lakes and transitional waters such as estuaries, rias, lagoons, etc.) and coastal waters up to one nautical mile offshore, or otherwise implement actions, termed 'measures', to bring them back to good status (Devlin et al., 2007). Notable exceptions to this rule include those 'heavily-modified water bodies' whose natural conditions have been substantially altered for essential uses such as irrigation, power generation and navigation (Borja and Elliott, 2007).

The ecological status of estuaries is classified according to the degree of deviation from appropriate reference conditions for a suite of physico-chemical, hydromorphological and biological 'quality elements' (Table 1), whereby the final classification (high, good, moderate, poor, bad) is determined by the element with the lowest status, according to the 'one out, all out' principle (Heiskanen et al., 2004; Borja, 2005). To meet WFD requirements, a multitude of approaches and indicators have been developed by EU Member States for assessing the ecological, and particularly the biological, status of estuaries, and methods developed for harmonising assessment outputs across jurisdictions (Table 1). In fact, the proliferation of these methods has been so extensive (Birk et al., 2012; Borja et al., 2012; Pérez-Domínguez et al., 2012) that some authors have questioned the need for further development of 'new' indicators (Diaz et al., 2004; Birk et al., 2012). The many achievements and limitations of the WFD are beyond the scope of this review, but have been summarised elsewhere (Hering et al., 2010; EEA, 2012; Reyjol et al., 2014).

2.3. South Africa

The National Water Act of 1998 (Act No. 36 of 1998) was the first piece of South African legislation to recognise water resources (including estuaries) as ecosystems, not just as a commodity for exploitation (Perissinotto et al., 2010). This was followed by the Integrated Coastal Management Act (Act No. 24 of 2008), which was gazetted in 2015 and requires the implementation of management and monitoring plans for each estuary in the country. Together, these Acts call for the classification of water resources and mandate reporting on the state of South African estuaries, thus giving rise to several new methods for assessing and classifying estuarine condition at various scales (e.g. Harrison et al., 2000; Adams et al., 2002; Harrison and Whitfield, 2006).

For example, an integrated Estuary Health Index (EHI), which considers both abiotic and biotic components, namely hydrology, mouth condition, water chemistry, sediment processes, microalgae, macrophytes, invertebrates, fish and birds (Adams et al., 2002; Table 1), was applied to 291 estuaries across South Africa as part of the 2011 South African National Biodiversity Assessment (Van Niekerk et al., 2013). For each component the current condition was estimated relative to the pristine state, and these estimates then weighted and aggregated to produce a composite health index score (Van Niekerk et al., 2013). The flexible, pragmatic approach of the EHI involved multidisciplinary groups of scientists assessing the health of a particular estuary using all available monitoring data, whilst relying on best professional judgement for data-poor systems. This approach provides a relatively rapid and cost-effective method for deriving comparable, national-level condition assessments, but has a potential danger of overreliance on expert judgement and qualitative information. Quantitative monitoring of abiotic and biotic parameters, across the full spectrum of near natural to heavily degraded estuaries in all three South African bioregions, is thus required to validate the findings of the 2011 assessment (Van Niekerk et al., 2013). Accordingly, a three-tiered National Estuaries Monitoring Programme, incorporating biotic and abiotic components, has been developed. Tier 1 monitoring commenced on 21 priority estuaries between 2012 – 2014 in collaboration with government conservation authorities, conservation forums and local and district municipalities (Cilliers and Adams, 2016).

2.4. Establishing evaluation criteria: common characteristics of successful international monitoring programs

The above developments in the USA, Europe and South Africa are not without their criticisms, including problems with integrating data from across multiple agencies and spatial scales (Lindenmayer and Likens, 2010), perceived weaknesses of the 'one out, all out' principle for combining multiple quality elements under the WFD (Borja, 2005), and the current overreliance of the South African national health assessment on expert judgement. Despite such criticisms, these international case studies consistently highlight many of the common characteristics of effective programs and methods for monitoring, assessing and reporting estuarine condition (e.g. Elliott, 2011). These attributes are listed, explained and exemplified in Table 1, and are considered in this review to represent aspects of current international best practice. We use these attributes as criteria against which approaches in Australia, or indeed any jurisdiction, may be evaluated.

3. Australia: historical context and national initiatives

Natural resource management in Australia has exhibited a trend towards larger and longer-term projects over the last two decades (Hajkowicz, 2009), coinciding with numerous initiatives for enhancing the integration, capacity and efficiency of management programs. In the following sections, we consider the historical context in Australia and evaluate some of the relevant initiatives and policies that have evolved or been proposed during this period.

3.1. Historical context: the need for a review of estuarine monitoring across Australia

In contrast to the international developments described above, Australian progress towards integrated and more holistic estuarine monitoring schemes has been erratic. The need for an ecologically holistic consideration of aquatic ecosystem health was acknowledged decades ago (e.g. ANZECC and ARMCANZ, 2000a, b), yet Australia has been comparatively slow to develop and implement bioassessment approaches for monitoring and managing estuarine condition (Barton, 2003; Beeton et al., 2006; Borja et al., 2012).

Other criticisms of Australian approaches to the assessment and management of estuarine condition have been raised consistently. Barton (2003) argued that, due to the lack of a coordinated national program in Australia, estuarine monitoring in Australia has been patchy, ad hoc, short term and predominantly undertaken in close proximity to major population centres and/or in estuaries with existing major issues. Similarly, Hirst (2008) concluded that there exists no coordinated national strategy for monitoring the status of marine and estuarine benthic habitats across Australia, with prevailing efforts often being fragmented and short term. This lack of coordination critically constrains efforts to conduct and report broad, regional-scale assessments of the condition of a range of habitats across Australia (Hirst, 2008), as highlighted in numerous State of the Environment (SoE) reports at both national and State levels (e.g. Beeton et al., 2006; EPA WA, 2007; CES VIC, 2008; NSW EPA, 2012). In a global review, Borja et al. (2008) similarly drew attention to a lack of direction and consistency among Australian approaches to ecological health assessment in general, compounded by confusion over State and federal responsibilities. More recently, Borja et al. (2012) noted that existing nationwide assessments of estuary condition throughout Australia continue to rely on qualitative criteria, with quantitative approaches being poorly developed.

Despite the above criticisms, Borja et al. (2012) also suggested that a large number of emerging projects and programs were likely to help fill identified gaps in the coming years. This review evaluates many of these emerging initiatives, most of which, as emphasised by Lindenmayer and Likens (2010), are only accessible through the grey literature. We focus first, in the following section, on national policies and initiatives relating to estuarine monitoring and reporting across Australia.

3.2. National policies, frameworks and legislation in Australia

The management of estuaries across Australia is governed by a wide array of national Acts and policies concerned with water extraction and use, development and planning, industrial compliance, navigation, fisheries, marine parks, specific habitats or protected species. To consider all of these is beyond the scope and intention of the review, and we will therefore focus on those national initiatives that are directly concerned with assessing and reporting estuarine condition.

3.2.1. National Water Quality Management Strategy

The Australian National Water Quality Management Strategy (NWQMS), first developed in 1992, aims to achieve sustainable use of the nation's water resources by protecting and enhancing their quality while maintaining economic and social development. The NWQMS comprises a set of policies, processes and guidelines, and includes two key documents, the Australian and New Zealand Guidelines for Fresh and Marine Water Quality ('the Water Quality Guidelines'; ANZECC and ARMCANZ, 2000a) and the Australian Guidelines for Water Quality Monitoring and Reporting ('the Monitoring Guidelines'; ANZECC and ARMCANZ, 2000b), both of which apply to estuaries.

The NWQMS advanced water resource management in Australia by defining 'protection of aquatic resources' as a core value and emphasising the need to sustain ecological health. For the first time in Australia, the Water Quality Guidelines explicitly identified the maintenance of 'ecological integrity' as a key objective for protecting aquatic ecosystems, mirroring the phraseology of the Clean Water Act in the USA. The NWQMS also aspired to create consistent and systematic monitoring practices across Australia (ANZECC and ARMCANZ, 2000b).

Despite its sound intent, the capacity of the NWQMS to incite change is limited given that, unlike the WFD or the Clean Water Act, it is not legally binding. Additionally, the guidelines are dominated by issues related to freshwater systems and, as the recommendations for estuaries are mostly based on large, well-mixed systems with permanent connections to the sea (Barton, 2003), they are largely unsuitable for the many small, stratified and periodically-open estuaries on Australia's south coast. Estuaries in northern Australia, including far northern WA, Queensland and the NT, were also underrepresented in the NWQMS, due largely to a lack of adequate baseline data. Moreover, although they encourage the use of biological components in aquatic monitoring programs (ANZECC and ARMCANZ, 2000a), the guidelines remain focused largely on issues of water quality.

3.2.2. State of the Environment reporting

Australia has undertaken national State of the Environment (SoE) reporting every five years since 1996, legislated under the Environment Protection and Biodiversity Conservation Act of 1999. However, the Act does not specify any regulations on the SoE reporting process or content, with reports often adopting a broad-scale, inventory-based approach due to a lack of detailed information and suitable indicators for assessing the condition of many ecosystems, greatly limiting the benefits for management (Borja et al., 2012). Recognition of this problem soon after the inception of SoE reporting precipitated an attempt to develop a national set of estuarine and marine indicators (Ward et al., 1998), though to date these have not been implemented consistently for monitoring estuarine condition. The 2006 national SoE report included strong statements on the need to collect long-term monitoring data, firmly emphasising that, rather than attempting to resolve long-standing systemic deficiencies (NLWRA, 2008), the future role of the SoE committee ‘should be one of data interpretation and commentary using accessible, up-to-date, relevant national data’ and that ‘The Australia State of the Environment 2006 report should be the last one that is prepared from a Committee-initiated process of *ad hoc* data collection’ (Beeton et al., 2006, p. vii). Nonetheless, these and other deficiencies, including issues around governance, legislation and funding to support the required monitoring, were also noted in the subsequent national SoE report of 2011 (State of the Environment 2011 Committee, 2011).

Most States and Territories within Australia also produce their own SoE reports, many of which explicitly consider the condition of their estuaries. This reflects the fact that the responsibility for monitoring and managing estuarine condition lies primarily with the States (State of the Environment 2011 Committee, 2011). Most have therefore selected appropriate indicators to inform their own SoE reports, and base these on available local to regional monitoring data.

3.2.3. National Land and Water Resources Audit

The first phase of the National Land and Water Resources Audit (NLWRA) delivered an assessment of Australia’s land, water and biological resources from 1997-2002. Its key aims included the development of a consistent national mechanism for collating information on natural resource condition, provision of this information to support national SoE reports, and development of assessment reports for Government (NLWRA, 2008). The 2002 assessment provided a national overview of the condition of Australia’s 979 estuaries (NLWRA, 2002a), the first stage of which categorised them into four classes – near-pristine (50% of estuaries), largely unmodified (22%), modified (19%) and extensively modified (9%) – based on a largely subjective assessment of known changes to the estuaries (i.e. estuary use, ecology, pests and weeds) and their catchments (i.e. natural cover, hydrology, land use, floodplain modification). Modified estuaries were then evaluated in more detail in a second stage of the assessment via a series of largely qualitative indices (of Ecosystem Integrity, Water and Sediment Quality, Fish Health, Habitat Condition, and estuary Utilisation and Susceptibility) to determine the relative extent of change from their condition prior to European settlement (NLWRA, 2002a).

Numerous criticisms may be levelled at the NLWRA, not least of which is the appropriateness of assessing condition against the baseline or reference state that would have been present prior to European settlement of Australia in the late eighteenth to mid-nineteenth centuries. The pristine estuarine condition that this represents is unobtainable in the presence of contemporary human populations and development, and so is of little practical use as a reference point for management (Kopf et al., 2015). As detailed quantitative data existed for only a handful of systems, the assessment process (as recognised within the report itself) also suffered from an over-reliance on qualitative evaluations and expert opinion and did not enable reliable benchmarks to be established (NLWRA, 2002a; Arundel and Mount, 2008). Moreover, a subsequent report has concluded that some of the estuaries deemed near-pristine in the first phase of the NLWRA will likely have to be reclassified due to inaccurate information at the time of the initial assessment (Murray et al., 2006). Finally, the scale of the NLWRA assessment also makes it poorly suited for addressing estuary management objectives at local and regional levels (Moss et al., 2006).

Notwithstanding these issues and problems, the first NLRWA report voiced many important criticisms of contemporary estuarine management practices and proposed numerous recommendations to address these failings. These included a need to clarify institutional and lead agency responsibilities for estuarine management at State and national levels, and to enhance monitoring and assessment of estuaries, including the selection and evaluation of suitable indicators for assessing estuarine condition and the collection of minimum data sets (NLWRA, 2002a, b). Numerous other valuable initiatives have arisen from, or been supported by, the second phase (2002–08) of the NLWRA. These include the establishment of the National Estuaries Network (NEN; http://www.ozcoasts.gov.au/nen.jsp) for estuary managers and an online, national estuaries database, which was conceived as Ozestuaries under the first NLWRA and updated in 2008 as OzCoasts (http://www.ozcoasts.gov.au/about/about.jsp).

3.2.4. Other initiatives

Several other attempts have been made to coordinate Australian monitoring and assessment under a common framework. These have included the National Natural Resource Management Monitoring and Evaluation Framework (NRMMC, 2003b) and the accompanying National Framework for Natural Resource Management – Standards and Targets (NRMMC, 2003a), and an integrated estuary assessment framework (IEAF; Moss et al., 2006) which aimed to explicitly link estuary condition to relevant stressors and pressures in order to identify the best indicators for informing management. Management responses within the IEAF are seen as a function of estuarine condition, the risks to the estuary as a result of its vulnerability to various stressors, and its community values. The IEAF is among the most complete of the national frameworks proposed for Australia’s estuaries to date, and offers tangible benefits for estuarine management and reporting at local and regional scales.

In recent years a National Estuarine Environmental Condition Assessment Framework (NEECAF) has also been proposed to provide direction for reporting on the broad ecological integrity of estuaries at a national level. This framework sought to align assessment programs across Australia to enable comparison of the condition of estuarine assets at regional, state and national levels (Arundel and Mount, 2008). The three layers (‘Passes’) of the NEECAF are similar in structure to the tiered approach of the US EPA (CRMSW, 2000), with priority estuaries being identified at each Pass so that subsequent, more data-intensive assessments are focused on progressively fewer estuaries (Arundel and Mount, 2008). Trialling of the NEECAF across several States demonstrated its potential to effectively translate state and regional reports into national-level information products (Mount, 2008).

None of the above proposed frameworks, however, have been implemented to date.

4. Conclusions

This first component of a broader review of Australian approaches for monitoring, assessing and reporting estuarine condition has established the broad national and international context in this field and identified ten key attributes of successful estuarine monitoring and reporting programs worldwide. These attributes relate to the context, objectives and design of monitoring programs, the monitoring elements and types of indicators that are employed, and the ways in which monitoring outputs should be reported, communicated and responded to. Together, they are considered to provide a set of globally-relevant ‘best practice’ criteria, against which Australian progress in this field can be evaluated.

There has been significant effort across Australia over the last one to two decades to better coordinate estuarine monitoring and assessment programs under a nationallycompatible and management-relevant framework. However, due largely to the responsibility for natural resource management being vested at the State level, and to the lack of any specific, overarching national legislation, there remains considerable divergence between States in the legal and/or policy requirements and approaches for monitoring, assessing and reporting estuarine health. Part two of this review examines recent, current and impending programs for understanding and reporting estuarine condition in each Australian State and Territory, and critically evaluates them against the above best-practice criteria.

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Figure captions

Fig. 1. Example reporting of national and regional coastal condition (including estuaries) across the United States, from the 2012 National Coastal Condition Report (US EPA, 2012).

Tables *(separate file, attached)*

Table 1

Attributes (evaluation criteria) of effective, fit-for-purpose programs for monitoring, assessing and reporting estuarine condition and trends.

Table(s)

Table 1 – Attributes (evaluation criteria) of effective, fit-for-purpose programs for monitoring, assessing and reporting estuarine condition and trends.

Evaluation criterion		Explanation and examples
Context, objectives and design of monitoring programs		
1	Monitoring and assessment is underpinned by the DAPSI(W)R(M) (i.e. Driver-Activity-Pressure-State Change-Impact (on Welfare)-Response (Measures) framework, or similar.	Human **Activities** and their underlying **Drivers** generate **Pressures** on ecosystems. Management **Responses** (often termed **Measures**) focus on minimising or mitigating the ecological **State Changes** and social **Impacts** (on human **Welfare**) that result from these pressures (Atkins et al., 2011; Barnard and Elliott, 2015; Wolanski and Elliott, 2015). Monitoring should incorporate measurable indicators for each relevant component of the framework, to establish causal relationships and allow the efficacy of management responses to be assessed and communicated (Borja and Dauer, 2008). *Examples: The US National Estuarine Eutrophication Assessment (NEEA) follows a Pressure-State-Response model (Bricker et al., 2003; 2007). The 2011 South African National Biodiversity Assessment (NBA) identified, ranked and mapped the numerous pressures on estuaries nationally, then correlated them with estuarine condition to identify key threats and management targets/responses (Van Niekerk et al., 2013).*
2	Monitoring and assessment addresses specific management objectives and forms an integral part of an adaptive management cycle.	Monitoring is a means to a management end and thus should address a specific and well-defined aim. Under an adaptive management cycle, monitoring outputs are used to evaluate the effectiveness of management measures for addressing specific objectives. Monitoring regimes and management responses are refined in light of these outputs, thus promoting greater accountability (Hajkowicz, 2009; Williams, 2011). *Example: Each of the 28 National Estuary Programs (NEP) across the USA is based on a Comprehensive Conservation and Management Plan (CCMP), which prioritises management activities, research, monitoring and funding for the estuary according to specific management needs with well-defined objectives (Imperial and Hennessey, 1996; LCREP, 2011).*
3	Monitoring addresses a legislated requirement for assessing and reporting estuarine condition and trends.	Legislative requirements for assessing and reporting estuarine condition have stimulated the development of novel techniques and coordination of existing approaches for assessing estuarine condition in various parts of the world (Gibson et al., 2000; Devlin et al., 2007), creating new funding opportunities for expanded monitoring and applied research (Hering et al., 2010; Birk et al., 2012, 2013). *Examples: Assessment, monitoring and reporting of estuarine condition are legally required under the US Clean Water Act (CWA), the European Water Framework Directive (WFD) and the South African National Water Act (NWA).*
Monitoring elements and indicators[a]		
4	Monitoring and assessment programs adopt an holistic view of ecological condition and employ relevant, cost-effective indicators of State Change, including physical and chemical water quality; sediment quality; habitats; key flora and fauna; and ecosystem processes/functions.	Relevant legislation in the US (CWA), Europe (WFD) and South Africa (NWA) has stimulated estuarine managers to adopt a broader, more holistic concept of estuarine ecological condition, rather than one based largely on water quality (Karr, 1991; Rapport and Hildén, 2013). *Examples: The US National Coastal Condition Assessment (NCCA) employs five indices of coastal and estuarine condition – water quality, sediment quality, benthic community condition, habitat and fish tissue contaminants (Borja et al., 2012). Similarly, multiple biological, physical, chemical and hydrological quality elements are used to assess estuary status under the WFD (Borja, 2005).*

Evaluation criterion		Explanation and examples
5	Monitoring and assessment programs employ indicators that are sensitive to changes in estuarine condition, i.e. they can detect ‘signals’ of anthropogenic pressure against the ‘noise’ of natural variability.	Disentangling natural spatio-temporal variability and other sources of uncertainty (‘noise’) from a genuine response (‘signal’) is critical for estuarine monitoring programs, particularly given the highly dynamic nature of estuarine environments (Elliott and Whitfield, 2011). Monitoring should therefore employ sensitive indicators with clear cause and effect relationships to relevant pressures, thus enabling management responses to target causal pressures and their consequent impacts (Dale and Beyeler, 2001). Sources of variability must also be quantified and accounted for in the design of monitoring programs and confidence levels of reporting outputs (Irvine, 2004; Carstensen, 2007). *Examples: Under the WFD, appropriate indicators are typically selected or validated using independent measures of estuarine condition or pressures (Perez-Dominguez et al., 2012), and reference conditions are commonly derived for each major region of an estuary to account for their natural spatial differences (Teixera et al., 2008). Estuaries are similarly divided into homogenous salinity zones for an Assessment of Estuarine Trophic Status (ASSETS) ranking under the US NEEA (Bricker et al., 2003; 2007), and the NCCA focuses on a standardized ‘index period’ to account for temporal variability when classifying benthic community condition and water quality (Jackson et al., 2000).*
6	Appropriate reference conditions, and scoring thresholds that distinguish condition classes and/or limits of acceptable change, are established for each indicator using objective, independent data on estuarine condition or anthropogenic pressure.	Boundaries (thresholds) between ecosystem condition classes should ideally be ecologically relevant, i.e. indicate perceived ‘tipping-points’ in estuarine condition, and relate to the specific management objectives (Birk et al., 2012). Classification of estuarine condition is typically achieved via comparison against a reference condition, which may be established from undisturbed control site(s) or, where these are not available or are inappropriate, via hindcasting, predictive modelling or best professional judgement (Gibson et al., 2000; Mee et al., 2008; Borja et al., 2009). The challenges of inappropriate or shifting baselines and the effects of climate change on reference conditions should also be considered (Mee et al., 2008; Kopf et al., 2015). *Example: Under the WFD, independent data on specific pressures are frequently used to set thresholds between Ecological Status classes (i.e. high, good, moderate, poor, bad) for each of the five Biological Quality Elements (Borja et al., 2007; Uriarte and Borja, 2009).*
7	Monitoring and assessment programs employ indicators that enable condition to be reliably compared among estuaries and allow for monitoring outputs to be ‘scaled up’ for reporting across multiple spatial scales, as required.	Comparability of estuarine monitoring and assessment schemes across large (regional to national) spatial scales is invaluable for broad-scale management prioritisation and reporting. Shared reference conditions (Borja et al., 2004; Harrison and Whitfield, 2006) or the ‘intercalibration’ of diverse assessment tools against common standards/benchmarks (Borja et al., 2007; Birk et al., 2013; Lepage et al., 2016) are required to enable such comparisons, and appropriate aggregation rules may enable condition assessments to be ‘scaled-up’ across broader geographical areas or management units (CRMSW, 2000; Borja et al., 2013; Barrett et al., 2015). *Examples: The USEPA is aiming to construct a modified, US-specific AMBI for nationwide application under the NCCA, to overcome difficulties in comparing benthic condition ratings between jurisdictions, each of which has historically employed regional/local indices that differ in their compositions and scoring systems (e.g. Weisberg et al., 1997). The WFD required member states to intercalibrate their national assessment methods to harmonise results and ensure consistent classification of water bodies across the EU (Poikane et al., 2014). Although criticised in the case of estuaries (Moss, 2008; EEA, 2012), this process has led to many novel advances, built capacity and ensured greater comparability of assessment methods among jurisdictions (Birk et al., 2013).*

Evaluation criterion		Explanation and examples
		Results of the 2011 South African NBA were aggregated for reporting at local to national scales, enabling all relevant management bodies to assess the effectiveness of their actions and prioritise future responses (Van Niekerk et al., 2013). The detailed, regional 'State of the Bay/Estuary' reports produced under the US NEP also inform national Coastal Condition Reports (US EPA, 2012).
Reporting, communicating and responding		
8	Monitoring and assessment outputs are integrated for reporting and decision-making purposes.	Integrating the outputs of multiple biotic and/or physico-chemical indicators of ecological condition into summative indices (Jordan and Vaas, 2000; Aubry and Elliott, 2006) or combining outputs via appropriate decision rules (Borja et al., 2013, 2014) allows for holistic assessment at the ecosystem level rather than of individual ecosystem components. This can simplify communication of monitoring outputs whilst retaining underlying, detailed information to inform specific management decisions (Dennison et al., 2007; Borja et al., 2012, 2016). *Examples: The South African Estuary Health Index integrates assessments of hydrology, hydrodynamics and mouth condition, water chemistry, sediment processes, microalgae, macrophytes, invertebrates, fish and birds (Adams et al., 2002), whilst the US NCCA combines separate indicators of water quality, sediment quality, benthic community condition, coastal habitat and fish tissue contamination to assess overall estuarine condition (US EPA, 2012).*
9	Reporting of monitoring and assessment outputs is conducted at relevant time scales, utilises formats suitable for the lay person/politician, and is widely accessible and publicised.	Within logistical and financial constraints, monitoring and assessment results should be reported with a frequency that aligns with management objectives to enable prompt evaluation of management efficacy and implementation of adaptive management responses. Additionally, monitoring outputs should be communicated broadly via a range of media, using non-technical summaries and/or simple, visual techniques to promote broader community understanding and support and better engage stakeholders (Dennison et al., 2007; Longstaff et al., 2010). *Example: The exemplary monitoring and reporting program for Chesapeake Bay (US) encompasses a range of communication products and methods for reporting to politicians, key stakeholders/industries and the wider community, e.g. see Longstaff et al. (2010).*
10	Monitoring and assessment outputs elicit a management response when limits of acceptable change (based on a target or thresholds) are exceeded.	As part of the adaptive management cycle, quantitative thresholds for the limits of acceptable change are established *a priori* for each indicator of estuarine condition. If those thresholds are exceeded, a planned management response (e.g. habitat restoration, water quality improvement measures) should be implemented in a timely manner to help address the impact and/or pressure (Jackson et al., 2000; de Jonge et al., 2006). *Example: As water bodies that fail to achieve Good Ecological Status under the WFD must be brought up to standard by programmes of measures, the boundary between Moderate and Good status provides a key threshold to determine the need for management responses (Rapport and Hildén, 2013). 'Thresholds of Potential Concern' have been established for relevant indicators of the condition of South African estuaries, exceedance of which prompts a management action (DWAF, 2008).*

[a] We define **elements** as the various components of the ecosystem whose condition is of interest (e.g. water chemistry, habitats, flora, fauna). The state of these elements can be assessed and reported using **indicators**, which may be single parameters (e.g. water temperature, dissolved oxygen concentration, seagrass density) or composite indices (e.g. the Water Quality Index of Pantus and Dennison [2005]).

Figure(s)

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